ARL-TR-8214 ● Nov 2017

US Army Research Laboratory

Investigation of Light-Emitting Diode (LED) Point Light Source Color Visibility against Complex Multicolored Backgrounds

by Jim Faughn, Paul D Fedele, Christopher Stachowiak, and Barry Vaughan

NOTICES

Disclaimers

ARL-TR-8214 ● NOV 2017

US Army Research Laboratory

Investigation of Light-Emitting Diode (LED) Point Light Source Color Visibility against Complex Multicolored Backgrounds

by Jim Faughn, Paul D Fedele, Christopher Stachowiak, and Barry Vaughan
Human Research and Engineering Directorate, ARL

REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED (From - To)**
November 2017	Technical Report	1 April 2014–30 September 2016

4. TITLE AND SUBTITLE
Investigation of Light-Emitting Diode (LED) Point Light Source Color Visibility against Complex Multicolored Backgrounds

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Jim Faughn, Paul D Fedele, Christopher Stachowiak, and Barry Vaughan

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
US Army Research Laboratory
ATTN: RDRL-HRB-A
Aberdeen Proving Ground, MD 21005-5425

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-8214

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
We evaluated the threshold visibility illuminance for signals sent from light-emitting diodes (LEDs) of 5 colors (green, red, white, amber, and blue). Experiment 1 involved controlled laboratory measurements of LED visibility against selected uniformly colored backgrounds. Experiment 2 involved outdoor measurements of LED visibility against camouflage patterns in natural daylight. Five camouflage patterns were used (MARPAT Woodland, Desert, and Navy, and Arctic and Swiss Alpenflage). These camouflages represent a variety of battlefield environments. Indoors, LEDs were displayed before 5 uniformly colored backgrounds selected to best match the combined chromaticity of the camouflages. Participants used the method of adjustment to vary the brightness of the LEDs until each LED color became barely perceptible, and barely imperceptible, providing visibility thresholds for each LED against each background. Results show the LED illuminance required to achieve threshold average visibility increases as background illuminance increases, the Arctic (white) backgrounds required the highest LED illuminance to achieve threshold visibility, and the red LED color was visible at the lowest illuminance against all background materials at the highest background illuminance values.

15. SUBJECT TERMS
LED, color visibility, illuminance threshold, environment background, luminance signal

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
					Paul D Fedele
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER (Include area code)**
Unclassified	Unclassified	Unclassified	SAR	50	410-278-5984

Contents

List of Figures

List of Tables

1. Introduction

The US Army Research Laboratory/Human Research and Engineering Directorate has measured the amount of light humans need to barely detect different colored LEDs against a variety of militarily relevant backgrounds.

The topic of human visual detection thresholds has been actively researched since the time of Ernst Weber, 1795–1878 (Watson 1963). It has been studied in a variety of tasks and contexts (e.g., Blackwell 1946; Foley and Legge 1981; Zuidema et al. 1984; Bruce et al. 2003). The literature cited previously focuses on thresholds for detection of achromatic or grayscale targets of discrete size, shape, and position in the visual field and also on the visual search process. However, multiple colors in complex geometries associated with camouflage backgrounds cause difficulty in drawing generalizable conclusions from visibility measurements. Complex backgrounds also cause modeling difficulties in creating widely applicable models of visibility. For these reasons, little work has succeeded in defining widely applicable metrics for the detection of a colored point source of light against complex, multicolored backgrounds, such as camouflage materials.

Our study has focused on foveal vision, including the foveal region and the central foveal region, which extend 3.0° from center and 0.6°s from center, respectively (Fulton 2009). Our interest is in steady point-sources of light, such as produced by a steady LED. Flash, motion, flicker, onset, size, shape, eccentricity, and retinal location (as applied to visual search) are not relevant.

Illuminance cast by a point source diminishes as an inverse function of the square of the distance. Although the illuminance changes, the color remains constant over distances as large as several kilometers. Color can change with distance over several kilometers, when haze and atmospheric scattering decrease the overall saturation of a color and increase the magnitude of short-wavelength (blue) light scattered into the line of sight from the intervening air (e.g., Troscianko et al. 1991), but this is not the case in our experiments. In our indoor experiments, all participants viewed the light sources at a fixed distance less than 20 m, while in outdoor experiments, all threshold observation distances were under 500 m. In our experiments, color changes with distance were assumed to be insignificant.

In this study, we determined the threshold-visible illuminances cast by LEDs of various colors placed in front of backgrounds of various camouflage materials, and composite-colored fabrics derived from the camouflage materials, when the backgrounds were illuminated by direct sunlight or other artificial lighting. These measurements are intended to provide information for signal generation processes,

making light signals visible at the greatest range, against the greatest number of relevant backgrounds, under bright, sunlit, background conditions.

2. Instrumentation and Facilities

Equipment and facilities used in the indoor and outdoor measurements are detailed in the following text.

A PR-745 SpectraScan Spectroradiometer (Photo Research Inc., Chatsworth, CA), was used to measure illuminance and color composition of the LEDs and camouflage and uniform color background materials. The spectroradiometer used is shown in Fig. 1.

Fig. 1 PR-745 SpectraScan Spectroradiometer used to measure light level and spectra of LEDs. Used with permission from Thamotharan, Jadu (Jadu.Thamotharan@photoresearch.com).

Sunlight illuminance levels were measured with a Konica Minolta T-10A illuminance meter (Konica Minolta Business Solutions USA, Inc., 7550 Teague Rd no. 401, Hanover, MD 21076), shown in Fig. 2.

Fig. 2 Konica Minolta T-10A illuminance meter. Used with permission from Kyle Drozenski (Kyle.Drozenski@konicaminolta.com).

A Titmus i500 vision testing device was used to screen the vision of test participants to ensure 20/40 Snellen acuity or better in all test participants.*

A Leica Rangemaster 1600-B laser rangefinder was used to measure the distance of each test participant from the LEDs and background material, at the point where the test participant determined the LED was at threshold visibility. The laser rangefinder is shown in Fig. 3.

Fig. 3 Leica Rangemaster 1600-B rangefinder. Used with permission from Brian Bell (brian@leicasportoptics.com).

The LEDs used in the study were 5050 SMD 3-chip LEDs with 120° viewing angles. They were wired with a series 220 Ohm resister for operation at 12 VDC. Specifications for colored and white LEDs are in Table 1.

* A picture of the Titmus i500 is available at http://www.lipindietz.com/i500%20vision%20tester.htm.

Table 1 Specifications of LEDs used in indoor and outdoor experiments

Colored LED specifications			
Color	**Current draw**	**Output (millicandelas)**	**Wavelength**
Red	15 mA	1200 mcd	635 nm
Amber	15 mA	1200 mcd	595 nm
Green	15 mA	3500 mcd	520 nm
Blue	15 mA	1000 mcd	465 nm

White LED specifications			
Color	**Current draw**	**Output**	**Effective color temperature**
Cool white	20 mA	4100 mcd	6000 K

The LEDs in outdoor measurements are shown in Fig. 4, against a black background. For outdoor measurements, camouflage materials were placed behind the LEDs in front of the black background. The black background was not used as a background for any visibility measurements.

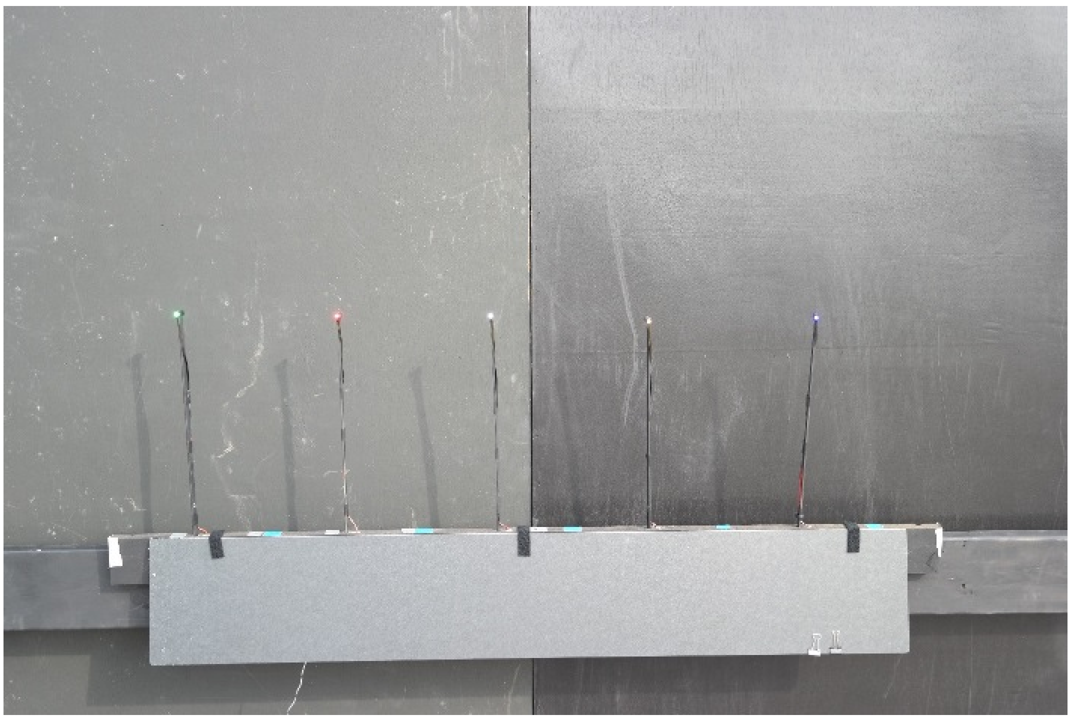


Fig. 4 LEDs used in outdoor experiments mounted in front of camouflage-supporting board

The LEDs were held in place at the end of 0.635-cm (1/4-inch)-wide metal rods. Rods were spray-painted black and the LED lead wires were fixed to the rods. For the outdoor trials, the LEDs were powered by a 12-V battery that was recharged every day. LED illuminance, at a fixed distance, was measured each day before and after outdoor measurements, and the average value was applied to assess threshold visibility for the day's measurements.

Figure 5 shows the LEDs in indoor measurements against the Arctic camouflage, which was a solid white fabric.

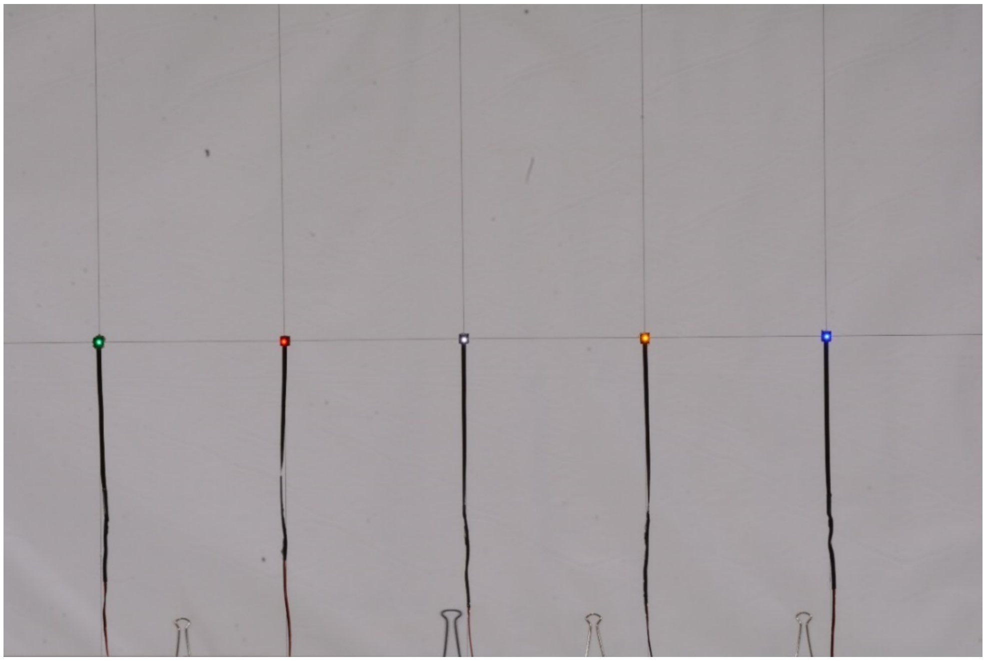


Fig. 5 LEDs used in indoor experiments mounted in front of Arctic camouflage (white) material

Photographic contrast and shading in Fig. 5 cause imprecise visual representation; the photographs are provided only for illustrative purposes and might not accurately represent colors and luminance levels.

The LEDs were held in place by fine wires (0.36-mm diameter) that can be seen in Fig. 5. The LED power wires were run up the LED support wires.

LED digital pulse-width modulators (PWMs) (dimmers) were used to adjust the luminance of the LEDs to threshold visibility in all indoor experiments. The modulators were LDKR-RGB6 PWMs with 3 pulse-width modulation circuits, shown in Fig. 6.

Fig. 6 LDKR-RGB6 PWMs with 3 pulse-width modulation circuits

Each PWM delivers a square-wave current at constant voltage for a precise, digitally controlled on/off time. A particular PWM setting provides a constant amount of ON-time per second, versus OFF-time per second, which determines the apparent LED brightness.

The indoor LEDs also were fitted with a custom-made spatial filter, which allows the light to show through a portal 1/32 inch in diameter and 2 layers of 50% neutral-density filter between the LED and light portal.

3. Method

Five LED colors—green, red, white, amber, and blue—were selected and used in this study.

Given the difficulties of measuring light visibility in actual battlefield environments, we made visibility measurements using camouflage materials as backgrounds because camouflage materials are created to have patterns of color and structure that visibly blend into actual battlefield environments. Camouflage patterns selected for this study were recommended by Lisa Hepfinger of the US Army Natick Soldier Research Development and Engineering Center, Natick, MA (Hepfinger 2015). The camouflage patterns used were 3 Marine Pattern (MARPAT) patterns (Desert, Woodland, and Navy), 1 Arctic camouflage material (uniform white fabric), and 1 camouflage pattern used by the Swiss Army: Alpenflage, which contains colors common in deciduous woodland fall foliage.

The study is composed of 2 experiments that use similar designs. Experiment 1 involved indoor measurements and determined visibility threshold illuminance for colored LEDs when viewed against 5 background color fields. The actual camouflage patterns were not used. Instead, background color fields were selected based on a blending of the colors in the actual camouflage patterns, as will be described. This experiment was performed indoors using 2 different values of background illumination.

Experiment 2 included outdoor measurements and determined visibility threshold illuminance for LEDs of the same colors as the indoor experiment, but the LEDs were viewed against actual camouflage patterns in a more realistic outdoor environment. The outdoor experiment provided a more direct measure of LED visibility thresholds in real-world environments and included bright sunlight conditions, which we could not achieve with indoor lighting.

In both indoor and outdoor measurements, the approach used to determine the 50% threshold illuminance of an LED-background pair was a version of the psychophysical Method of Adjustment (Stevens 1958), in which an observer

controls the intensity of a stimulus until it is just barely detectable or just barely not detectable. Specifically, the observer either adjusts a clearly detectable stimulus downwards in intensity until it just barely cannot be detected, or adjusts a clearly nondetectable stimulus upwards in intensity until it just barely can be detected. In Experiment 1 participants adjusted LED intensity directly by means of a PWM dimmer. Dimmers were used because we could only use a limited distance between the participant and the LEDs. In Experiment 2 (the outdoor measurements), the intensity of the physical LED was held constant and the observers physically moved toward or away from the LED until individual LEDs became just barely visible, when approaching the LED, or became just barely no longer visible, when receding from the LED. Outdoors, much greater distances could be used to achieve threshold visibility across different test subjects and it became unnecessary to vary the power of the LEDs.

In both experiments, the order of background and LED presentation was based on the 5 × 5 Latin Square (Box et al. 1978; Williams 1949), shown in Table 2.

Table 2 A 5 × 5 Latin Square for determining order of blended background color (Experiment 1) or background camouflage pattern (Experiment 2). For solid colors the camouflage is replaced by the composite color that represents that camouflage.

	First Background	Second Background	Third Background	Fourth Background	Fifth Background
Order 1	Desert	Navy	Alpen	Woodland	Arctic
Order 2	Navy	Alpen	Woodland	Arctic	Desert
Order 3	Alpen	Woodland	Arctic	Desert	Navy
Order 4	Woodland	Arctic	Desert	Navy	Alpen
Order 5	Arctic	Desert	Navy	Alpen	Woodland

Both indoor and outdoor experiments used 2-factor designs. Independent variables included the following:

- LED Color: Five levels (green, red, white, amber, blue)
- Background Pattern: Five levels (MARPAT Woodland, MARPAT Navy Blue, MARPAT Desert, Arctic, and Swiss Alpenflage)

Indoor and outdoor experiments also included the following co-variable:

- Illuminance on the background material (determined by a measured outdoor sunlight condition and a measured indoor lighting condition).

Indoor experiments added the following co-variable:

- Chromaticity difference between the LED and the background material (dependent on lighting condition).

All test participants provided measured threshold values for all LED and background fabric conditions. Within-subject analysis was not used because our objective was to assess if any color was more visible against the background material to people overall.

3.1 Indoor Measurements

Indoors measurements were made in Building 518, Aberdeen Proving Ground, where light levels could be controlled across sessions and participants.

In our indoor experiments, we did not use actual camouflage materials as backgrounds. Rather, each LED was viewed against 5 uniformly colored fabrics. The uniformly colored fabrics were used indoors because in early piloting trials outdoors at the maximum achievable indoor distances (under 20 m), we found that LED visibility depended on precisely which color swatch of each camouflage pattern was behind the LED. For outdoor measurements, we were able to locate the camouflages far enough away from the observers that the camouflage color precisely behind the LED was not clear. This could not be achieved indoors, so uniformly colored fabrics were used.

The uniformly colored fabrics used indoors were selected by measuring the color composition of each camouflage, using the calibrated spectrophotometer and a wide 30° field of view. The spectroradiometer provided a set of coordinates for the measured light in color space coordinates. These coordinates were input and combined in Adobe Photoshop, transferred to Microsoft Paint, and printed on a Hewlett Packard Color LaserJet Printer CP4525. We recognized that the perceived color of the printouts could change with printer characteristics, the illuminating spectrum, and the color sensitivity of the individual viewing the color, so we examined the color printouts against the camouflages at 100 m and selected the best-matching color and locally procured the best-matching colored fabrics by consensus, with customer approval.

For the indoor measurements, rather than having the test participant dim and brighten the LEDs by moving farther away from, or closer to, the LEDs, we measured LED illuminance as a function of the digital setting displayed on an adjustable digital PWM used to power the indoor LEDs. To determine LED threshold visibility illuminances in the indoor experiments, the test participant remained sitting at a fixed distance from the LEDs. The trial began with each LED at its maximum illuminance. The participant then reduced the brightness of the LED, one at a time, by rotating the PWM dial for each LED. PWM dials were located on a small stand in front of the participant. The participant reduced the intensity of the LED until they could just barely no longer see the LED against the

background. We then recorded the digital setting on the PWM. Participants were allowed to take their time in determining when they could no longer see the LED, but they were also told to move the PWM only toward lower (dimmer) settings, and not move it up and down in making the threshold determination. After each LED was adjusted to where the participant could no longer see each LED, all the PWMs were dimmed to the minimum visibility, to ensure that no LED could be seen. The test participant then increased each PWM setting until the participant could again just barely see the corresponding LED, and we recorded the digital PWM setting.

In the indoor measurements, we used both neutral density filters and custom 3-D printed pinhole apertures to reduce the maximum LED output. Preliminary investigations indicated that this adjustment helped to center average LED threshold visibility values near the center of the adjustment range of the PWMs, for the background lighting levels available in the indoor facility. Using the recorded PWM settings, we determined the illuminance of each LED at threshold visibility by using a measured calibration curve for each LED. Using the calibrated spectrophotometer, LED illuminance was measured as a function of PWM setting and the function was used to determine the threshold visibility illuminance of each LED. The LED calibration curves were measured using the neutral density filters and the custom 3-D printed apertures on each LED.

Indoor measurements were conducted in the east end of Building 518, in an open, high-bay research area. The room has approximately 43 ft, 4 inches × 56 ft, 4 inches of floor space. The apparatus for Experiment 1 and the fixed-observation location were positioned at opposite diagonal corners of the room, resulting in a distance of 50 ft from the test participant's location at the control console to the LED target grids and 56 ft to the background boards. The participant sat in one corner before a control console and viewed directly toward the target grid that held the LEDs in front of surrogate camouflage background. The presentation order of the LEDs was green, red, white, amber, and blue, as viewed from left to right, and the LEDs were positioned at 5 ft, 1-1/2 inches above floor level.

The illumination of the backgrounds was adjusted to accommodate the test participant's ability to see each LED at its maximum luminance. Background materials were illuminated by ceiling lights, 4 portable quartz 500-W halogen flood lights, and 2 high-power 30-W red, green, blue (RGB) LED flood lights. The LED flood lights each produced 750 lm with a total power consumption of 30 W, and measured 22.5 cm (8.88 inches) × 18.7 cm (7.39 inches) × 12.7 cm (5.01 inches). If the participant could not see all the LEDs at their maximum dimmer settings, the 4 portable quartz 500-W halogen flood lights were turned off. All lights together (ceiling lights, portable quartz 500-W flood lights, and 2 high-power 30-W RGB LED flood light fixtures) produced an illuminance on the background materials of

4,250 lm/m^2 (395 fc). Without the 4 portable quartz 500-W halogen flood lights, the background illuminance was 264 lm/m^2 (24.5 fc). The luminance of each background was measured with, and without, the 4 portable quartz 500-W halogen flood lights, to determine visibility as a function of background luminance and color content.

Solid-colored backgrounds were used indoors as surrogates for the camouflage patterns used in the outdoor measurements. Because the indoor distance between the participant and the camouflage pattern was relatively short compared with the achievable outdoor distances, the camouflage patterns still had visible areas of light and dark coloring. Preliminary testing determined that using camouflage patterns at short-viewing distances could lead to situations where an LED could sometimes appear directly in front of a dark region of the pattern, thus increasing visibility, while other times the LED could appear in front of a light region, thus reducing visibility. In discussion with OWL program office representatives, it was decided to eliminate this source of variance in the indoor measurements by representing each camouflage pattern as if the pattern was viewed at a distance great enough to blend the individual elements into one overall color. For example, the Woodland pattern might be represented as a field of uniform olive drab color.

Background fabric colors were selected from a "blend" of the colors in contents of the corresponding camouflage pattern. Blended-background colors were generated by measuring the color coordinates of the camouflage pattern using the model PR-745 SpectraScan Spectroradiometer to measure the color content in a circle of approximately 76 cm (30 inches) in diameter on each camouflage pattern at a distance of approximately 50 ft. The International Commission on Illumination (CIE) 1931 XYZ color space coordinates (Smith and Guild 1931) were converted to RGB color coordinates (Süsstrunk et al. 1999) and these values were used to generate a color sample in Photoshop. This sample was then transferred to Microsoft Paint and printed, giving a sample of the blended color.

We then affixed the blended-color sample to the camouflage pattern and viewed the camouflage pattern and the solid-color sample in natural outdoor lighting at distances of 200 m, where the camouflage pattern appeared to blend into a single color. We used visual perception to verify that the color sample matched the blended-camouflage pattern.[*]

No composite color was needed for the Arctic camouflage because the Arctic camouflage was a uniform white fabric.

[*] The color samples were then visually color matched as closely as possible to solid-color fabrics available and purchased from Jo-Ann Fabrics and Crafts, 615 Bel Air Rd Ste F, Bel Air, Maryland.

Table 3 describes the solid colors that were determined to be best matches to the 5 camouflage patterns.

Table 3 Mapping between camouflage patterns (used in outdoor Experiment 2) and best-matching solid color composites (used in indoor Experiment 1)

Camouflage pattern	Described best-matching solid color based on photometry of camouflage pattern
MARPAT Navy	Gray
MARPAT Woodland	Olive
MARPAT Desert	Light tan
Arctic	White
Swiss Alpenflage	Brown

Color differences, or contrasts, can contribute to visibility, so in the indoor measurements we included chromaticity analysis in this study to determine if detectability is significantly influenced by chromaticity differences, beyond the influence of luminance differences.

In the following, we show examples of colors and photographs of colored materials. In all photographs and figures, color presentations are limited by photographic and display characteristics. Color presentations may not be accurately displayed; they are shown only as qualitative illustrations.

Chromaticity quantifies the color of frequency-distributed visible light. Chromaticity is quantified by the *x* and *y* coordinates of the CIE xyY color space. These coordinates are normalized by overall luminance (Y), so they are independent of the overall perceived brightness material. The coordinates *x* and *y* of the CIE xyY color space give the color composition, or chromaticity, of the illuminated background composite fabric. Chromaticity details are available from Fairman et al. (1997).

As a convenient reference, a color diagram of the CIE xyY chromaticity plane is shown in Fig. 7.

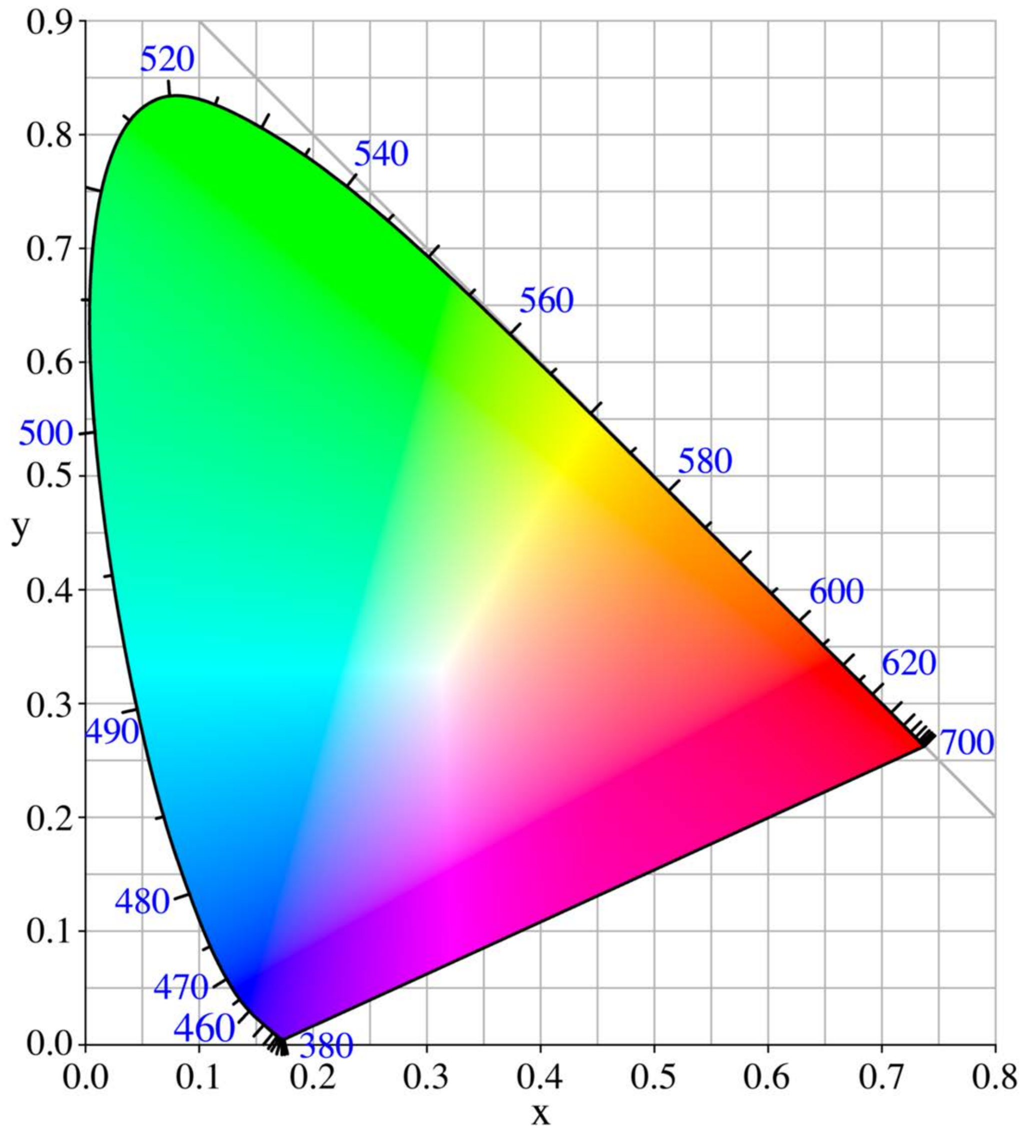
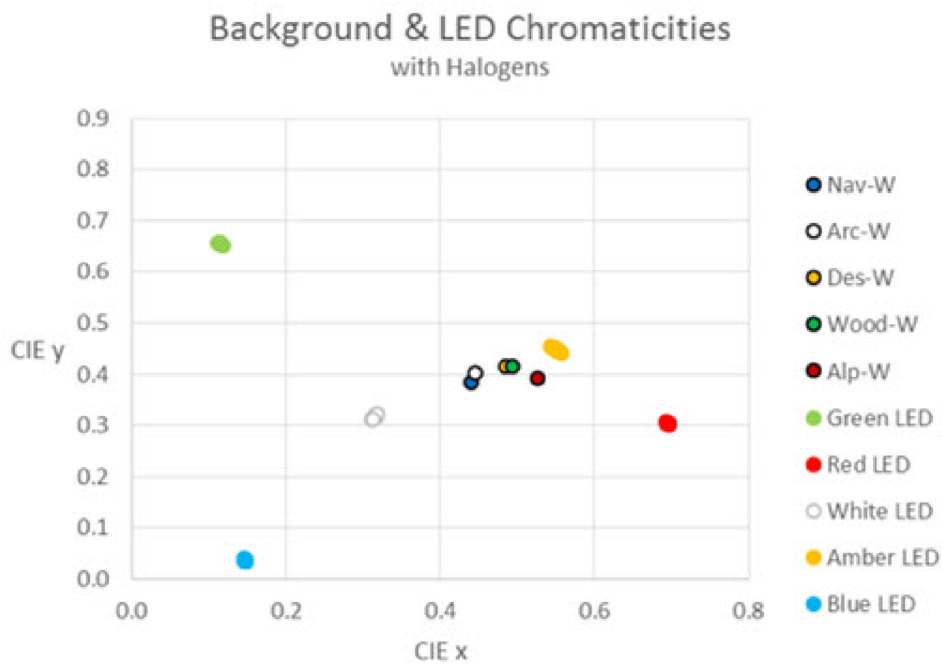


Fig. 7 CIE xyY chromaticity plane showing pure single-wavelength (nanometers) colors distributed about the edge of the colored region. (Adapted from https://upload.wikimedia.org/wikipedia/commons/b/b0/CIExy1931.png).

The wavelength and chromaticity coordinates of monochromatic light are shown along the outer edge of the colored section in Fig. 7.

For the 2 indoor lighting conditions, measured CIE xyY color coordinates, *x* and *y* of each composite fabric are plotted in Figs. 8a and 8b. Chromaticity values plotted in Fig. 8a were measured with lighting condition 1, which used minimal ceiling lighting, 4 portable quartz 500-W halogen flood lights, and 2 high-power 30-W RGB LED flood light fixtures. Values plotted in Fig. 8b were measured with lighting condition 2, which included minimal ceiling lighting and 2 high-power

30-W RGB LED flood light fixtures; the 4 portable quartz 500-W halogen flood lights were not used in condition 2. Measured LED chromaticities are also plotted.



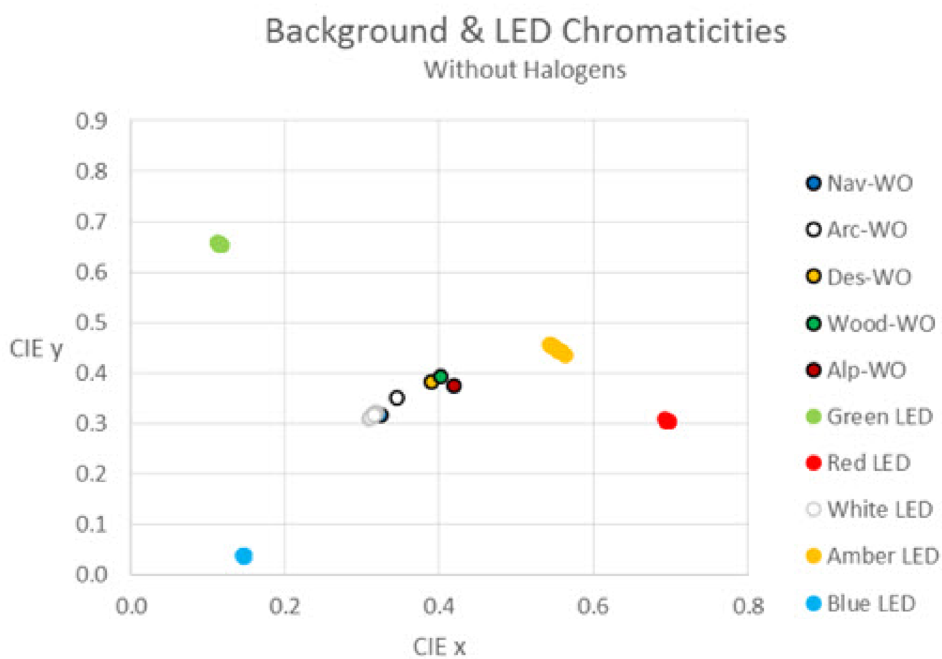


Fig. 8 Measured CIE xyY chromaticity coordinates of composite fabrics using lighting condition 1 and LED chromaticities

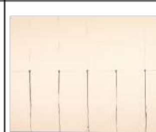
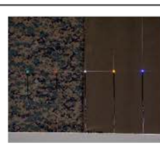
In Figs. 8a and 8b, composite fabric chromaticity points are shown with black surrounding borders. LED chromaticities are also plotted for each of the threshold

visibility values assessed in the indoor measurements. We observe small variations in some LED chromaticity due to measurement error in the calibration expressions derived from LED illuminance measured for various PWM settings. The measured LED calibration expressions are given in the Appendix.

For the amber LED, the derived functions giving the CIE Tristimulus values (X,Y,Z) as a function of the PWM setting, show the smallest R^2 values of any of the LED calibration expressions. Figures 8a and 8b illustrate that the amber LED shows the largest variation in chromaticity across the threshold visibility illuminance values. However, this variation is negligible because it is smaller than any color difference between the amber LED and any other measured chromaticity.

For convenient comparisons, Table 4 shows camouflages in relatively uniform outdoor sunlight conditions and color-composite materials with their respective camouflage materials in each of the indoor lighting conditions. Although background illuminance was measured for the outdoor measurements, chromaticity variations with changes in outdoor cloud cover and lighting conditions were not determined and the light conditions pictured in Table 4 are shown only as a relative illustration.

Table 4 Photographs of camouflages under outdoor sunlight and camouflages and color-composite materials under indoor light conditions 1 and 2

Camouflage Name	MARPAT Woodland	MARPAT Navy	Arctic	MARPAT Desert	Alpenflage
Sunlight					
Light Condition (1)					
Light Condition (2)					

The lighting sources used in outdoor and indoor experiments are summarized as the following:

- Outdoors: Sunlight
- Indoors: Lighting condition 1; minimal ceiling lighting, 4 portable quartz halogen 500-W flood lights, and 2 high-power 30-W RGB LED flood light fixtures.
- Indoors: Lighting condition 2; minimal ceiling lighting, and 2 high-power 30-W RGB LED flood light fixtures; no portable quartz halogen 500-W flood lights

Comparing Figs. 8a, 8b, and Table 4, it can be seen that the 4 portable quartz 500-W halogen flood lights caused a relative shift of the indoor composite fabric chromaticities of approximately 0.1 units in the positive x-direction and 0.03 units in the positive y-direction; the portable quartz halogen 500-W flood lights increased the yellow and red-yellow luminance of the composite fabrics and the camouflage materials.

3.2 Outdoor Measurements

Outdoor measurements were made on a paved drive between Buildings 520 and 503, Aberdeen Proving Ground.

For each LED color and each background camouflage material, we made 2 measurements for estimating the threshold illuminance of the LED for each test participant. For the first measurement, the test participant started close enough to the LEDs and camouflage backgrounds so that all the LEDs were easily and clearly visible to the test participant. The participant then walked away from the LEDs and background and indicated when he or she could no longer see one of the LED colors. Participants were allowed to take their time in determining when they could no longer see the LED, but they were also told to move only away from the LEDs and not to go back and forth in making the threshold determination. We measured and recorded the distance at which that LED produced threshold illuminance against that background for that participant. After the last LED could no longer be seen, the test participant walked an additional distance (typically 20 paces) farther away from the LEDs and background, and the participants checked to ensure they could not see any LED. Test participants then walked toward the LEDs and indicated when they could just barely see each LED color. Again, participants were allowed to take their time in determining when they could see the LED, but they were also told to move only toward the LEDs and not to go back and forth in making that threshold determination. We measured and recorded that distance, as a second measure of the distance at which that LED produced threshold illuminance against

that background for that participant. One approaching and one receding measurement were made for each LED against each camouflage background.

To quantify visibility threshold illuminance for an LED against a given camouflage background in the outdoor experiments, each LED's illuminance intensity, L_0, was measured at a measured distance, using the calibrated spectrophotometer. A photopic filter was used to limit the measured light to the amounts of light that define brightness to the human eye (illuminance).

With the LED illuminance intensity, L_0, at a known distance, R_0, and the threshold visibility at another distance, R_T, we determined the threshold illuminance intensity, L_T, for that participant and that LED against that background, as

$$L_T = \left(\frac{R_0}{R_T}\right)^2 L_0. \quad (1)$$

Outdoors, LEDs were powered by a 12-V rechargeable battery. LED illuminance was measured each day, before and after performing outdoor measurements, and the average LED illuminance was used to assess the LED threshold visibility illuminance for the day's measurements. Overall, LED illuminance changed from the beginning of the day's testing to the end of the day's testing less than 1%.

Threshold visibility measurements under bright, sunlit conditions are most important in determining signal visibility because these measurements indicate the luminance required to ensure signal's visibility in brightly lit conditions. Outdoor testing took advantage of bright daylight conditions. Indoor lighting only produced a maximum background illuminance of 4250 lm/m^2 (395 fc) on the background materials. Sunlight produced a maximum background illuminance 96,800 lm/m^2 (8990 fc). Illuminance levels were measured with the illuminance meter.

Sunlight levels changed with the weather conditions during the outdoor trials. We did not have the capability to continuously monitor sunlight illuminance values and time-stamp the values to each threshold determination. When a Konica meter was used, sunlight illuminance values were measured up to 10 times per trial, depending on how much the cloud cover and lighting conditions appeared to vary during the trial. Measurements were made at times close to threshold determinations, but cloud cover and lighting conditions changed rapidly in some cases. To account for changing cloud cover and lighting conditions, illuminance measurement values were categorized by our perception of the cloud cover and the lighting conditions, and to each threshold determination, we applied the measured illuminance value corresponding to the cloud cover and lighting conditions judged closest to the conditions at the moment of the threshold determination. We also attempted to collect outdoor measurements on brightly sunlit days; we were not always

successful. A histogram, produced with Microsoft Office 2013 Excel, shows all recorded sunlight illuminance values in Fig. 9.

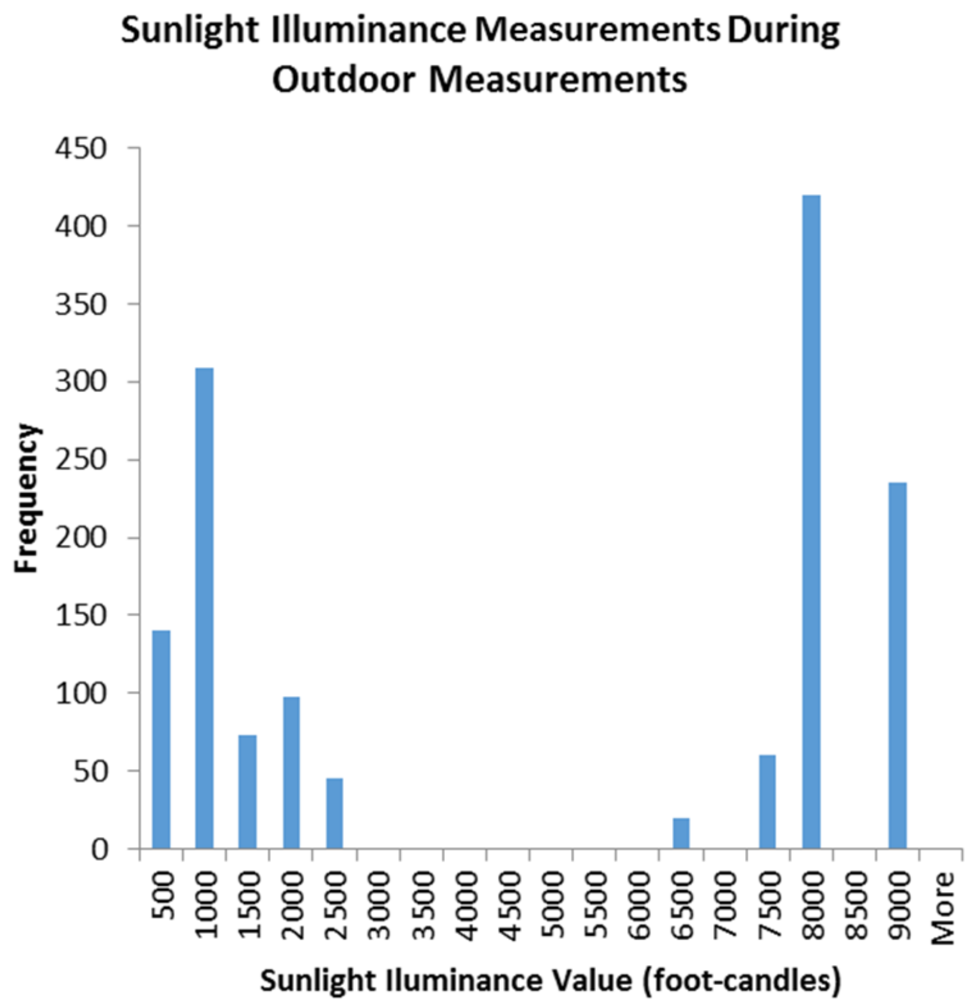


Fig. 9 Histogram of all sunlight illuminance values used in outdoor testing

The maximum sunlight illuminance was 8990 fc and the minimum sunlight illuminance was 220 fc. The median value is over 7000 fc.

The target holder boards consisted of 2 1.22- × 2.44-m (4- × 8-ft) sheets of plywood stood upright and painted flat black, with a weighted base attached for stability in light winds. The 2 boards were clamped together to form one continuous 2.44- × 2.44-m (8- × 8-ft)-flat black background. The LED target array was attached to a shelf made of a 2 × 4 board and a 2 × 6 board. The shelf was attached to the target boards, placing the LEDs 1.33 m (52 1/2 inches) above ground level. The shelf also held the camouflage-covered boards. The camouflage materials were attached to 1/2-inch foam core boards 1.22 × 1.63 m (4 × 5 1/3 ft) and these boards sat on the shelf behind the LEDs. These boards were secured at the top to the frame by a 2 ×

4 board clamped to the target holder board and held the camouflage panels securely and flatly against the target holder board.

The same LED light sources (5050 SMD 3-chip LEDs with 120° viewing angles) were used in the indoor and outdoor trials. Outdoors, no neutral density or spatial filters were used. LEDs were wired with a series 220-Ω resister for operation at 12 VDC. Refer back to Table 1 for LED specifications.

The LEDs were mounted onto small 3-D printed mounting tabs affixed to 30-cm long, 1.25- × 5-mm metal bars pressed into holes in the wooden shelf. The 5-mm sides of the metal bars were positioned on edge, with the 1.25-mm sides facing the participant, to minimize visual distractions and shadows against the camouflage backgrounds. The LEDs were mounted from left to right, ordered as green, red, white, amber, and blue. The order of LEDs remained constant throughout outdoor and indoor testing. All 5 LEDs were controlled by a single digital PWM dimmer, which was set at maximum intensity for all trials.

For the outdoor tests, prior to and after collecting data, the luminance of each LED in the test array was measured with the spectroradiometer to determine each LED's light level for the day's trials. The average of the measured values was used to determine the illuminance at threshold visibility for each threshold distance measurement.

The outdoor testing display is shown in Fig. 10, with the MARPAT Navy camouflage pattern.

Fig. 10 Outdoor testing display shown with the MARPAT Navy camouflage pattern and illuminated LEDs

LEDs did not present the same number of lumens. The luminance of each LED was measured each day, allowing us to evaluate the LED illuminance at the distance of the observed threshold visibility. The illuminance of each LED at a known distance was measured before and after each day of data collection, and the average value was used to determine threshold visibility illuminances for that day's measurements. Illuminance values of each LED used in outdoor testing are given in the Appendix.

The 5 camouflage patterns selected for this study—MARPAT Woodland, MARPAT Navy, MARPAT Desert, Arctic, and Alpenflage—are shown in sunlight in Figs. 11–15.

Fig. 11 The MARPAT Woodland camouflage

Fig. 12 The MARPAT Navy camouflage

Fig. 13 The MARPAT Desert camouflage

Fig. 14 The Arctic camouflage

The Arctic camouflage is a solid white material.

Fig. 15 The Alpenflage camouflage

The Alpenflage camouflage pattern was not available in bulk material. To measure LED visibility against Alpenflage camouflage, we obtained 4 Alpenflage-patterned jackets, zipped them together using their front zippers, and clipped each jacket to the foam core backboard used to hold the camouflage materials. The size of this panel was reduced to 74 × 163 cm (29 × 64 inches) to accommodate the size of the jackets without showing white foam core behind the camouflage material.

The outdoor test course used in this experiment is a concrete driveway and roadway allowing a clear visual path to the test display over a distance of approximately 500 m. A view of the test display from approximately 200 m is shown in Fig. 16.

Fig. 16 The outdoor test course with a 200-m view of the outdoor test display

In Fig. 16, the test display is shown with the MARPAT Desert camouflage pattern located between Building 502 (white) on the right and the edge of Building 520 (brick) on the left.

Participants could move as much as 500 m from the test display, as shown in Fig. 17, taken from the same position as Fig. 16, but facing away from the test display.

Fig. 17 The far end of the outdoor test course, viewed 200 m from the outdoor test display, facing away from the test display

The test course runs north and south. The test display was placed at the north end of Building 520 and faced south to take advantage of midday sunlight conditions. Sunlight levels changed during the study and were measured during each trial. For testing, we desired, but did not always achieve, bright sunlight conditions. The photographs in Figs. 16 and 17 were taken on a cloudier day.

4. Test Participants

Twenty-eight test participants took part in the outdoor study and 30 test participants took part in the indoor study. Twenty-seven participants took part in both the indoor testing and the outdoor testing. The number of participants needed for testing was estimated using a power analysis (Faul et al. 2007), based on guidance from Wu and Tian Y (2014), and recommendations from Ray et al. (2014). Participants had normal color vision and at least 20/40 Snellen visual acuity, corrected or uncorrected. Participants wore any vision correction required for their distance vision but did not wear tinted or photo-darkening lenses (e.g., Transition lenses, Transitions Optical, Inc.).

5. Analysis and Results

Indoor experiments measured the pulse-width modulation setting when a participant reported a particular color LED became nonvisible while decreasing the

LED duty cycle and when the particular color LED became visible when increasing the LED duty cycle. Illuminance on the background was also measured for both indoor background lighting conditions (Table 4). The PWM settings were subsequently converted into threshold luminance (CIE X,Y,Z) values, using the measured LED calibration functions. The threshold illuminance values (CIE X,Y,Z) were transformed into threshold chromaticity and illuminance values (CIE x,y,Y). Threshold illuminance values (CIE Y) were transformed into natural logarithms for further analysis. The logarithm of the luminance was selected for analysis instead of the illuminance because the illuminance is a positive-definite quantity, defined only for positive values and is poorly represented by a normal distribution. Rather, distributions of threshold illuminance values show log-normal characteristics. Differences between the threshold LED (x,y) chromaticity and background (x,y) chromaticity were calculated as the Euclidian distance between points on the CIE chromaticity plane.

Outdoor experiments measured the distances where the participants reached threshold visibility for each LED against each background. Throughout the outdoor experiments, it was evident that background illuminance values strongly influenced LED threshold visibility. To account for changing cloud cover and lighting conditions, sunlight illuminance on the background was measured and evaluated as previously described. From the average LED illuminance measured for each day's trials, the distance measurements were used to determine LED threshold illuminance for each distance measurement. Again, the natural logarithm of the illuminance was used for further statistical analysis. Chromaticity measurements for camouflage background materials were not made in the outdoor testing.

The measured threshold visible illuminance values were gathered across participants to determine the average threshold visible illuminance for each color against each camouflage material (outdoor measurements) and each background material (indoor measurements), at various values of background illuminance. Measurements and calculated data visibility threshold values and background illuminance values are available upon request to the authors. Statistical analyses and analysis plots were obtained using IBM SPSS Statistics.*

5.1 Threshold Visible Illuminance by LED Color and Background Fabric Material

Indoor measurements of visibility illuminance show how much visible light is needed to see each color LED against each composite-colored background. The indoor LED threshold visible illuminance significantly depends on LED color,

* IBM Corporation, 1 New Orchard Road. Armonk, New York, 10504-1722.

F(4, 1474) = 258, $p < .001$, and background material, F(4, 1474) = 4.58, p = 0.001. No significant overall interaction between LED color and background material is observed, F(16, 1474) = 0.85, p = 0.627. Estimated differences between the threshold visible illuminances are shown in Fig. 18.

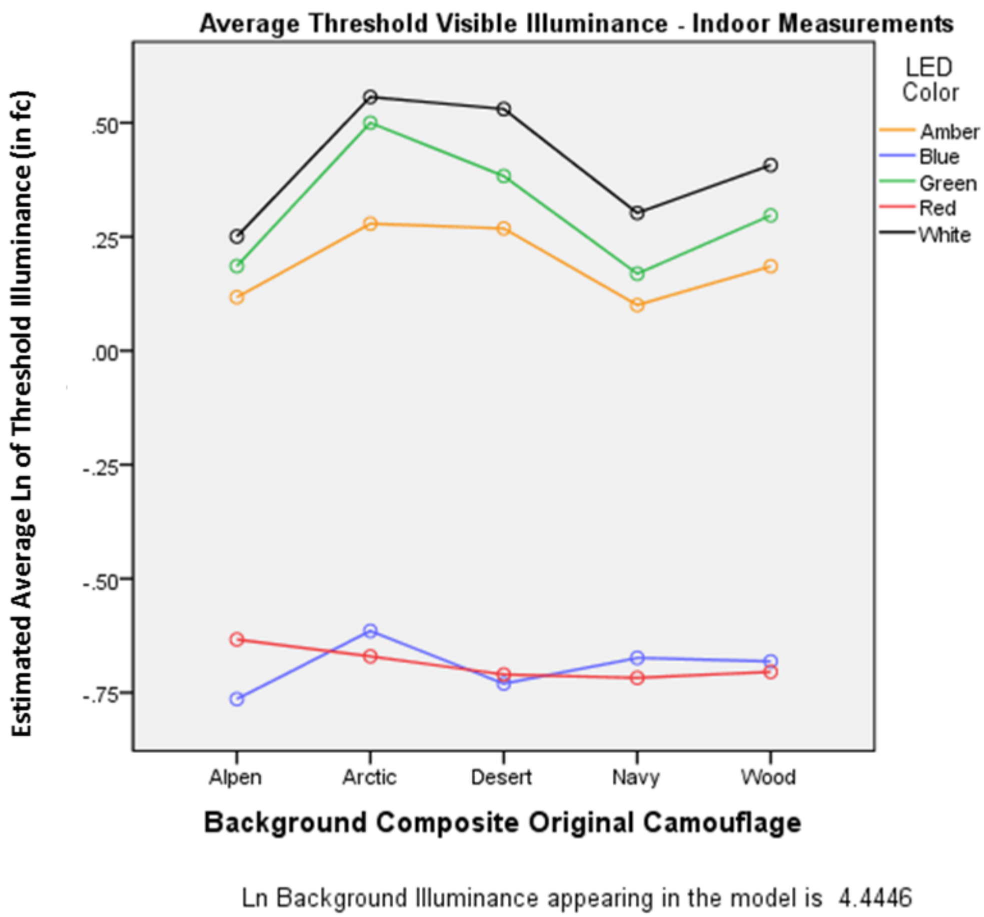


Fig. 18 Estimated natural logarithms of average LED threshold visible illuminances for each LED color against each composite-fabric background

Figure 18 shows that the red and blue LEDs were visible at the lowest illuminance values in the indoor experiments. Although the x-axis does not represent a continuous variable, a line plot is selected to help support the visual grouping of the natural logarithm values of the threshold visible illuminance within each LED color.

Background illuminance is treated as a covariate in Fig. 18. Two values of background illuminance were used in the indoor tests: 4250 lm/m^2 (395 fc) with all background lights, and 264 lm/m^2 (24.5 fc) with all background lights but the 4 portable quartz 500-W halogen flood lights. The average threshold illuminance

logarithms in Fig. 18 are determined for a background illuminance value of 917 lm/m^2 (85.2 fc).

Outdoor measurements were made with much higher values of background illumination than those used in the indoor measurements. Outdoor measurements of threshold visible illuminance show that much higher illuminance values are needed to see each color LED against each camouflage background under higher background illuminance conditions.

For the camouflage materials, the threshold visible illuminance of each LED significantly depends on LED color, $F(4, 143.0) = 69.8$, $p<0.001$, and background material, $F(4, 23.4) = 44.99$, $p<0.001$. Again, no significant interaction is observed between background material and LED color, $F(16, 86.5) = 1.234$, $p = 0.259$. Estimated average outdoor threshold visible illuminance values are shown in Fig. 19.

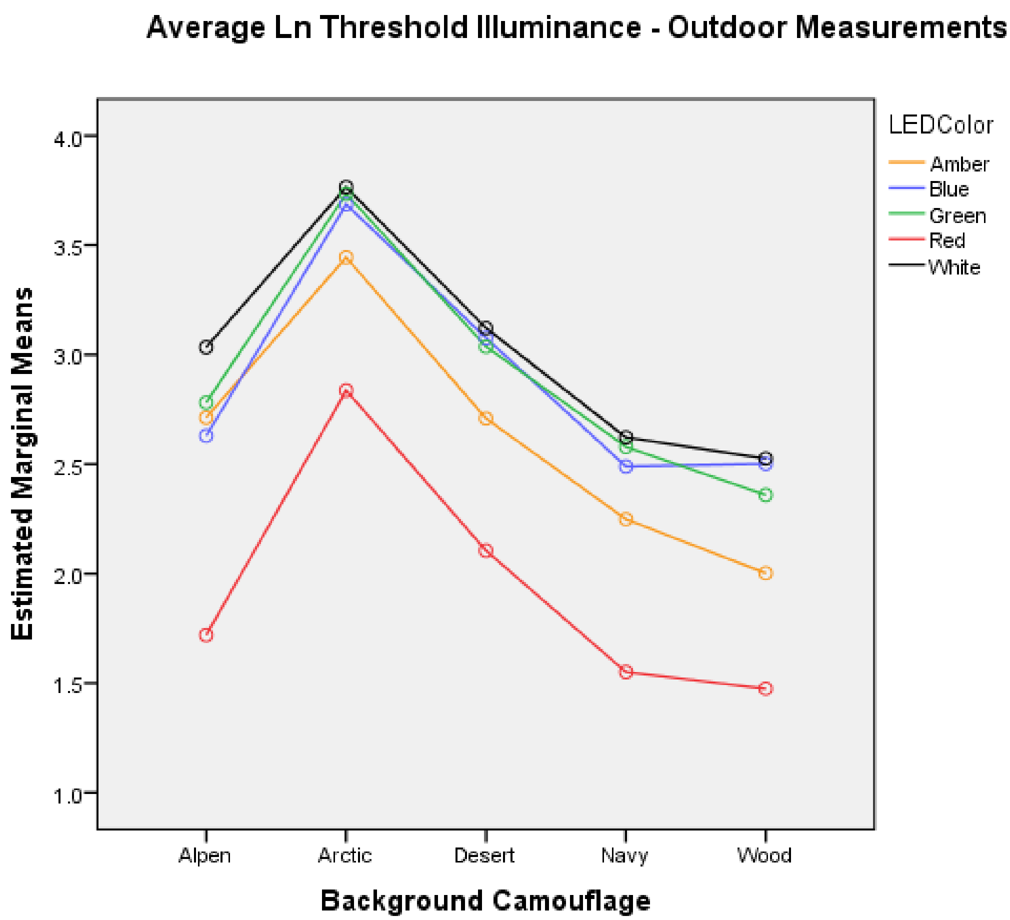


Fig. 19 Estimated natural logarithms of average LED threshold visible illuminances for each LED color against each camouflage background

Approved for public release; distribution unlimited.

In the indoor measurements, red and blue LEDs were visible at similar illuminance levels, while in outdoor measurements, red was visible at lower illuminance values than blue. Background illuminance values were much higher in the outdoor measurements than in the indoor measurements. Sensitivity to blue light increases under lower light conditions, as described by the Purkinje effect (Barlow 1957). We did not further investigate the observed relative change between red and blue. The outdoor threshold measurements show red remains visible at the lowest illuminance levels in outdoor sunlight conditions.

Figure 19 shows that Arctic camouflage—a solid white background—requires the greatest values of LED illuminance to ensure the LED remains visible against brightly illuminated backgrounds.

Figure 20 shows the dependence of LED visible illuminance at the different levels of background illuminance for all measurements: both indoors and outdoors.

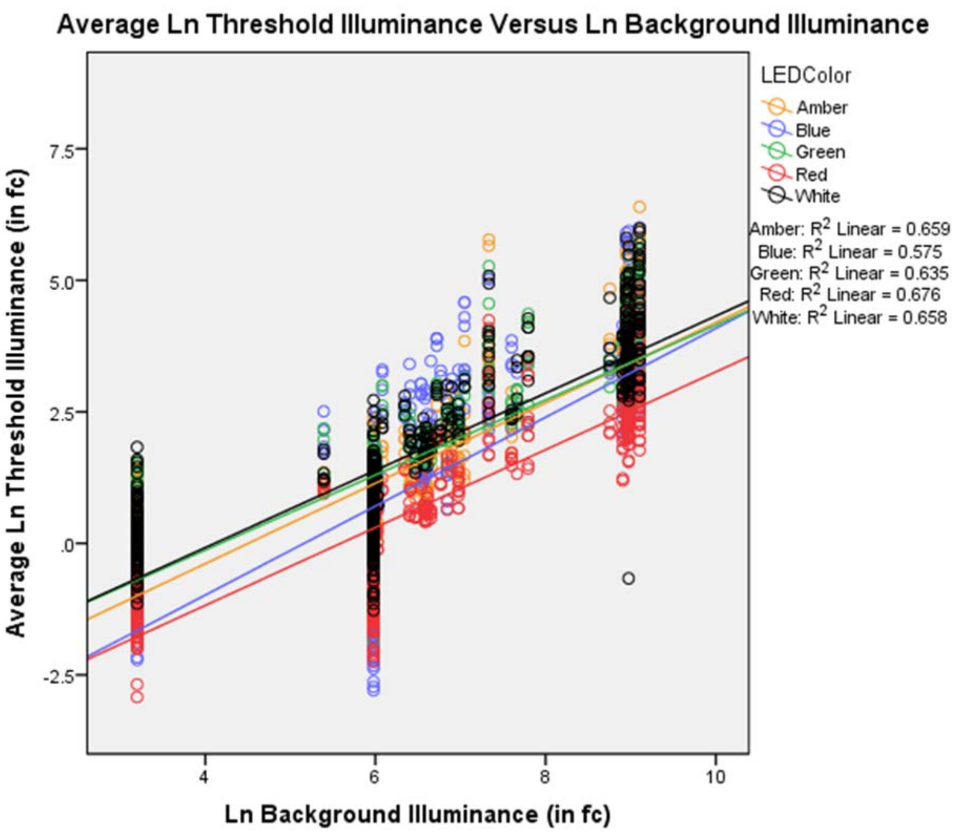


Fig. 20 Dependence of LED threshold visible illuminance at the different levels of background illuminance for all measurements

Figure 20 shows that the red LED is visible at the lowest illuminance under the highest background illuminance conditions. The lowest indoor lighting condition, at a value of the natural logarithm of the background illuminance in foot-candles of

3.20, used primarily the LED flood lights, which produced a solar spectrum. (This value of background illuminance is 264 lm/m^2, or 24.5 fc.) Ceiling lighting produced minimal illumination of the background materials. Indoor threshold visible illuminance measurements, at a value of the natural logarithm of the background illuminance in foot-candles of 5.97, were performed with additional quartz halogen flood lights. (This value of background illuminance is 4250 lm/m^2, or 395 foot-candles.) The quartz halogen flood lights did not produce a solar spectrum (Figs. 8a, 8b, and Table 4). As Fig. 20 shows, threshold visible illuminance values measured for natural logarithm of the background illuminance in foot-candles of 5.97 depart from the line showing visibility against backgrounds illuminated with a solar spectrum.

Analysis of the threshold visible illuminance of the LEDs against actual camouflage materials under high-sunlight background illuminance shows that red LEDs have the lowest threshold visible illuminance against all camouflage backgrounds.

5.2 Distance of LED Visibility vs. Outdoor Background Illuminance

Across all camouflage materials, the outdoor distances of visibility are plotted with SPSS in Fig. 21.

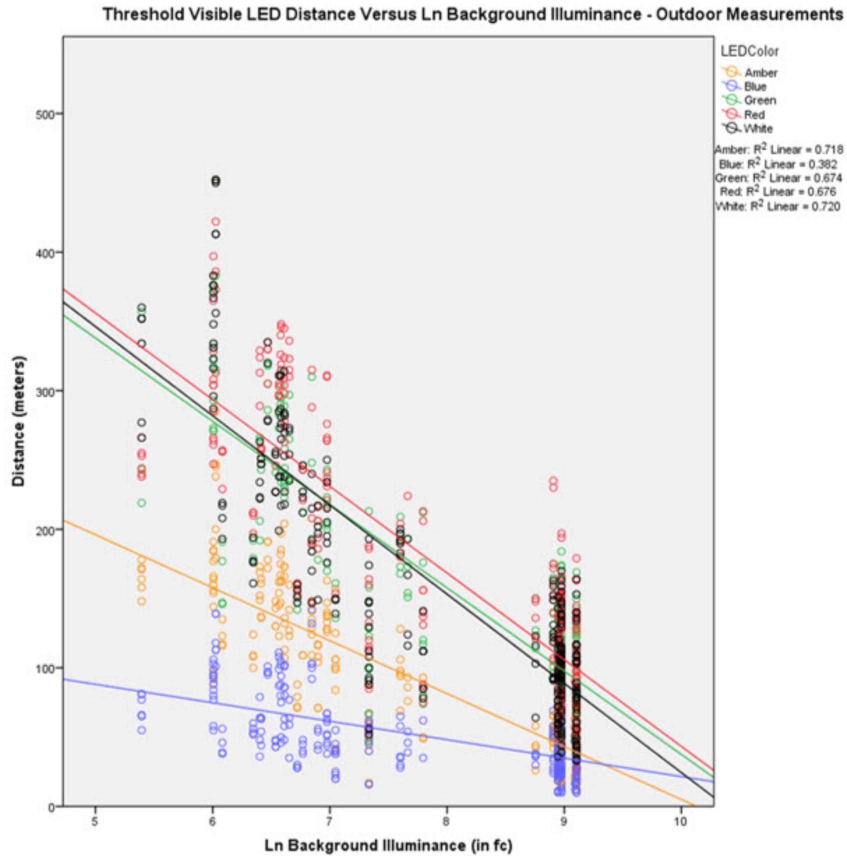


Fig. 21 Distance of LED threshold visibility vs. logarithm of outdoor background illuminance in foot-candles

Outdoor measurements show that the distance over which the LEDs can be seen significantly depends on LED color, background material, and background illuminance. Distance depends on LED color ($F(4, 1375) = 167$, $p<0.0005$), camouflage background material ($F(4, 1375) = 43.7$, $p<0.0005$), and background illuminance ($F(31, 137) = 15.1$, $p<0.0005$).

Recall all LEDs did not produce the same luminance. Thus, distance is not a direct measure of each LED's threshold visible illuminance. However, Fig. 21 shows that when all LEDs are powered by the same voltage (12 V), the red LED is visible at the greatest distances.

We made no efforts to optimize the design of the LEDs used in this study. However, presuming that the LED design and manufacturing process was engineered to produce bright LEDs as inexpensively as possible, in applying LEDs as the light source for a visual signal process, it is valuable to know if the red LED is visible at the greatest average range. In a signal application, if the power source has a fixed voltage and the LEDs have design and production characteristics similar to the LEDs used in this study, the red LED should maximize the range of LED visibility.

In this study, red LEDs were visible under bright sunlight conditions at an average distance of 100 m, across all background camouflage materials.

6. Conclusion

In summary and conclusion, we provide a relation between LED visibility at a field range, R_{field}, and LED illuminance measured in the laboratory at a distance, R_0'. This relation provides a method of determining how bright an LED must be in a laboratory measurement, at a distance of R_0', to achieve threshold visibility at a field range of R_{field}.

We compiled a table of LED threshold visible illuminance values for each LED color and background, based on threshold measurements under a range of the highest background illuminance values observed in this study. The threshold visible illuminance measurements, $I_{Thrshld}$, in this table can be used to estimate the signal illuminance, I_{Lab}, measured in a laboratory at a distance R_0', needed to allow the signal to be visible against each camouflage background, illuminated with direct sunlight, at a field range R_{Field}.

The signal illuminance, I_{Lab}, measured in a laboratory, needed to achieve threshold visibility at a field range, R_{field}, is the following:

$$I_{Lab} = I_{Thrshld} \times \left(\frac{R_{Field}}{R_0'}\right)^2. \qquad (2)$$

Table 5 gives the average threshold visible LED illuminance, $I_{Thrshld}$, for each LED color against each background, from all outdoor threshold measurements made with background illuminances greater than 79,440 lm/m^2 (7380 fc).

Table 5 Average threshold visible LED illuminance, $I_{Thrshld}$, for each LED color against each background for all background illuminances greater than 79,440 lm/m^2 (7380 fc)

$I_{thrshld}$	Background camouflage				
LED color	**Alpen**	**Arctic**	**Desert**	**Navy**	**Woodland**
Amber	627	1970	540	315	225
Blue	334	1274	363	217	242
Green	542	1487	499	299	247
Red	178	565	209	102	106
White	572	1795	576	369	295

When an LED casts an illuminance of this value at any range, our measurements indicate that the LED will be at average threshold visibility when viewed against a background similar to those in the table, illuminated directly by sunlight.

As an example for the stationary source, consider the following:

For a red LED to be visible at a range, R_{Field} = 100 m, against a sunlit woodland background, the LED must produce an illuminance, I_{Lab}, equal to = 42,400 lm/m^2 (3940 cd/m^2), when measured in the laboratory at a distance, R_0' = 5 m.

The values in Table 5 can be used to guide LED color selection in designing signal light sources and to estimate the brightness that an LED requires to achieve average threshold visibility at various field ranges against battlefield background consistent with the applied camouflage materials.

The results of this study may not generalize well to moving LEDs because current visual theories (Kleinholdermann et al. 2009) contend that the neurological motion-sensitive pathway requires a luminance difference defined by the chromatic sensitivities of the long-wavelength cones and the medium wavelength cones, whereas the neurological pattern-sensitive pathway does not require such a chromatic difference (Dobkins and Albright 1995). This indicates that although the stationary LED light source may be visible against the background, if the source is moving perpendicular to the viewing direction, the source may be harder to see. Trials with moving sources could be used to further address the visibility of moving sources.

7. References

Barlow HB. Purkinje shift and retinal noise. Nature. 1957 Feb 2;179(4553):255–256.

Blackwell RH. Contrast thresholds of the human eye. Louis Comfort Oyster Bay (NY): Tiffany Foundation; 1946.

Box GEP, Hunter WG, Hunter SJ. Statistics for Experimenters. New York (NY): John Wiley & Sons, Inc.; 1978.

Bruce V, Green PR, Georgeson MA. Visual perception: Physiology, psychology, & ecology. Psychology Press; 2003.

Dobkins KR, Albright TD. Behavioral and neural effects of chromatic isoluminance in the primate visual motion system. Visual neuroscience. 1995 Mar;12(2):321-32.

Fairman HS, Brill MH, Hemmendinger H. How the CIE 1931 color-matching functions were derived from Wright-Guild data. Color Research & Application. 1997;22(1),11–23.

Faul F, Erdfelder E, Lang AG, Buchner A. G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behavior Research Methods. 2007;39:175–191.

Foley JM, Legge GE. Contrast detection and near-threshold discrimination in human vision. Vision Research. 1981;21(7):1041–1053.

Fulton JT. Processes in Biological Vision. Corona Del Mar (CA): Vision Concepts; 2000 Aug 01 (cited 2016-08-31). 2009. [updated 2009 Jul 01; accessed 2017 Aug 09] http://neuronresearch.net/vision/reading/foveola.htm.

Hepfinger L. US Army Natick Soldier Research Development and Engineering Center, Natick, MA. Personal communication, 2015 Feb 6 Feb.

Kleinholdermann U, Franz VH, Gegenfurtner KR, Stockmeier K. Grasping isoluminant stimuli. Experimental brain research. 2009 Jul 1;197(1):15-22.

Ray DM, Roediger PA, Neyer BT. Commentary: three-phase optimal design for sensitivity experiments. Journal of Statistical Planning and Inference. 2014;149:20–25.

Smith T, Guild J. The CIE colorimetric standards and their use. Transactions of the Optical Society. 1931;33(3):73.

Stevens SS. Problems and methods of psychophysics. Psychological Bulletin. 1958;55(4):177–196.

Süsstrunk S, Buckley R, Swen S. Standard RGB color spaces. In Color and Imaging Conference. Society for Imaging Science and Technology. Jan 1999;1999(1):127–134.

Troscianko T, Montagnon R, Le Clerc J, Malbert E, Chanteau P-L. The role of colour as a monocular depth cue. Vision Research. 1991;31(11):1923–1929.

Watson R. The great psychologists: from Aristotle to Freud. 2nd ed. Philadelphia (PA): JB Lippincott Company; 1963. p. 234–241.

Williams EJ. Experimental designs balanced for the estimation of residual effects of treatments. Australian Journal of Scientific Research. Ser. A 2. 1949:149–168.

Wu CFF, Tian Y. (2014). Three-phase optimal design of sensitivity experiments. Journal of Statistical Planning and Inference. 2014;149:1–15.

Zuidema P, Roest W, Bouman MA, Koenderink JJ. Detection of light and flicker at low luminance levels in the human peripheral visual system. I. Psychophysical experiments. Journal of the Optical Society of America. 1984;1(7):764–777.

Appendix. Light-Emitting Diode (LED) Calibration with Pulse-Width Modulators (PWMs)

A.1 LED Calibration with PWM Settings

The International Commission on Illumination (CIE) XYZ color coordinates of the light-emitting diodes (LEDs) were calibrated for pulse-width modulators (PWMs) by measuring the CIE XYZ coordinates at 5 PWM settings, subtracting background CIE XYZ values measured with the LED turned off, and fitting the measured values with a quadratic expression for the CIE coordinate.

With the PWM setting, *m*, the expression for the CIE X, Y, or Z coordinate, labeled *W*, is

$$W = A \cdot m^2 + B \cdot m \,.$$

The following pages show calibration data and curves for each LED used in the indoor study.

White LED calibration measurements are in Table A-1.

Table A-1 White LED calibration measurements

White LED PWM setting	CIE Tristimulus values X	Y	Z
255	2609	2607	3243
200	1716	1716	2112
150	1024	1025	1248
100	491	492	592
50	144	145	172

The graph and curve fits for the white LED are shown in Fig. A-1.

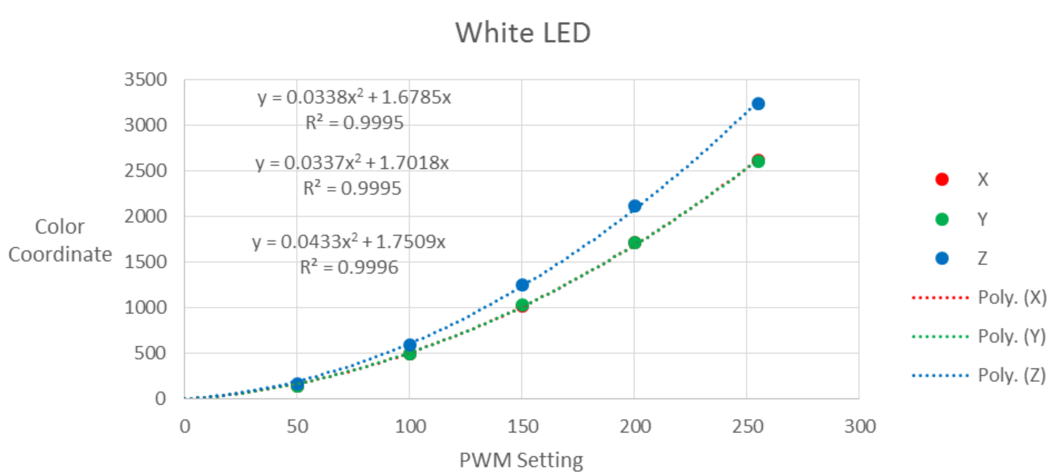


Fig. A-1 White LED calibration curves and quadratic curve fits with R^2 values

Figure A-1 shows the quadratic fit expressions that give the LED CIE XYZ coordinates for the LED at variable PWM settings. CIE XYZ coordinate expressions are given in the order y = X, y = Y, and Y = Z.

Amber LED calibration measurements are in Table A-2.

Table A-2 Amber LED calibration measurements

Amber LED PWM setting	CIE Tristimulus values X	Y	Z
255	2397	1839	5.11
200	1651	1281	3.55
150	1012	794	2.17
100	519	412	1.20
50	156	125	0.36

The graph and curve fits for the amber LED are shown in Fig. A-2.

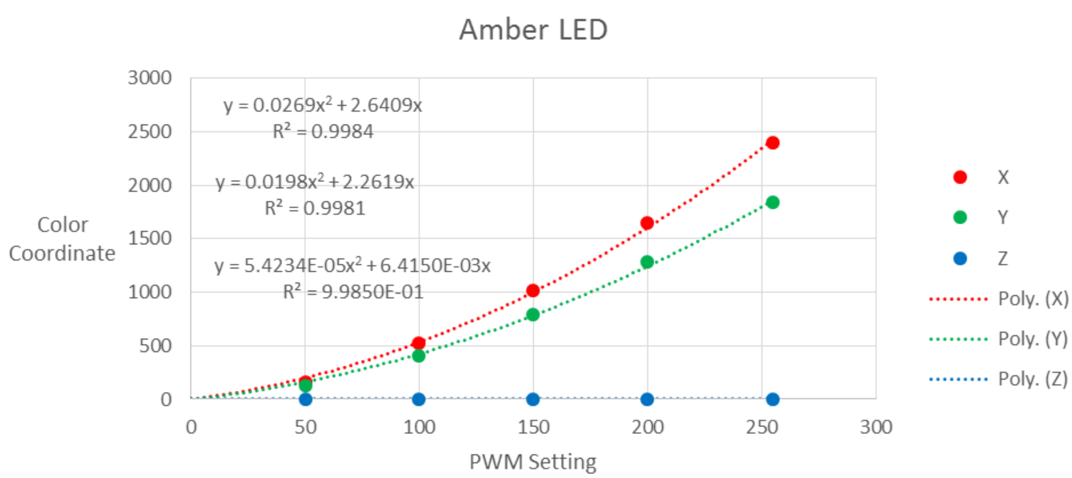


Fig. A-2 Amber LED calibration curves and quadratic curve fits with R^2 values

Figure A-2 shows the quadratic fit expressions that give the LED CIE XYZ coordinates for the LED at variable PWM settings. The CIE XYZ coordinate expressions are given in the order y = X, y = Y, and Y = Z.

Blue LED calibration measurements are in Table A-3.

Table A-3 Blue LED calibration measurements

Blue LED PWM setting	CIE Tristimulus values X	Y	Z
255	795	212	4455
200	523	136	2923
150	316	80	1764
100	155	39	864
50	44	11	247

The graph and curve fits for the blue LED are shown in Fig. A-3.

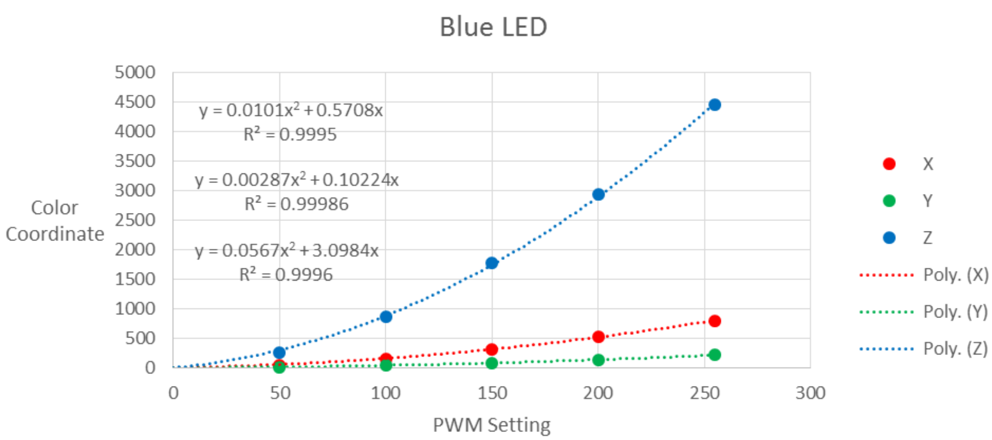


Fig. A-3 Blue LED calibration curves and quadratic curve fits with R^2 values

Figure A-3 shows the quadratic fit expressions that give the LED CIE XYZ coordinates for the LED at variable PWM settings. The CIE XYZ coordinate expressions are given in the order y = X, y = Y, and Y = Z.

Red LED calibration measurements are in Table A-4.

Table A-4 Red LED calibration measurements

Red LED PWM setting	CIE Tristimulus values X	Y	Z
255	1418	614	1.71
200	942	408	1.11
150	583	254	0.72
100	289	126	0.27
50	88	39	0.05

The graph and curve fits for the red LED are shown in Fig. A-4.

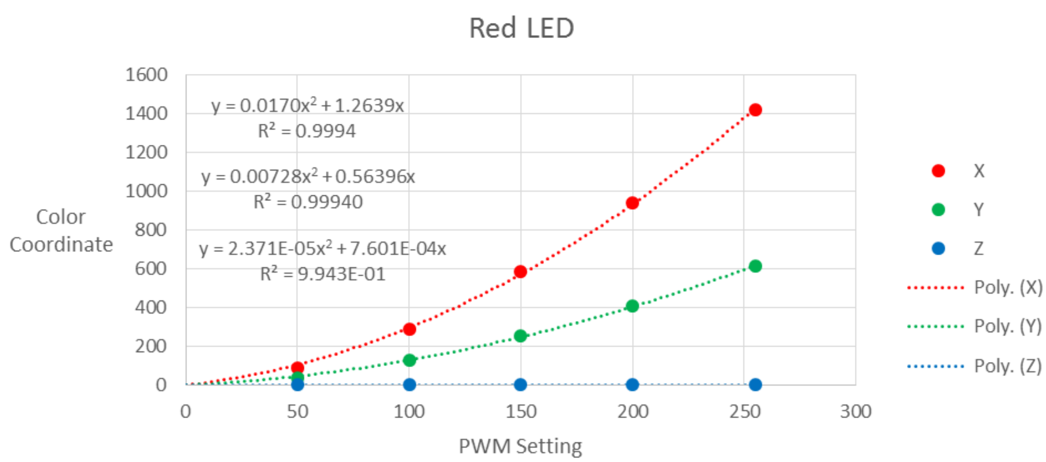


Fig. A-4 Red LED calibration curves and quadratic curve fits with R^2 values

Figure A-4 shows the quadratic fit expressions that give the LED CIE XYZ coordinates for the LED at variable PWM settings. The CIE XYZ coordinate expressions are given in the order y = X, y = Y, and Y = Z.

Green LED calibration measurements are in Table A-5.

Table A-5 Green LED calibration measurements

Green LED PWM setting	CIE Tristimulus values X	Y	Z
255	302	1645	581
200	197	1073	378
150	115	636	224
100	55	307	108
50	17	94	33

The graph and curve fits for the green LED are shown in Fig. A-5.

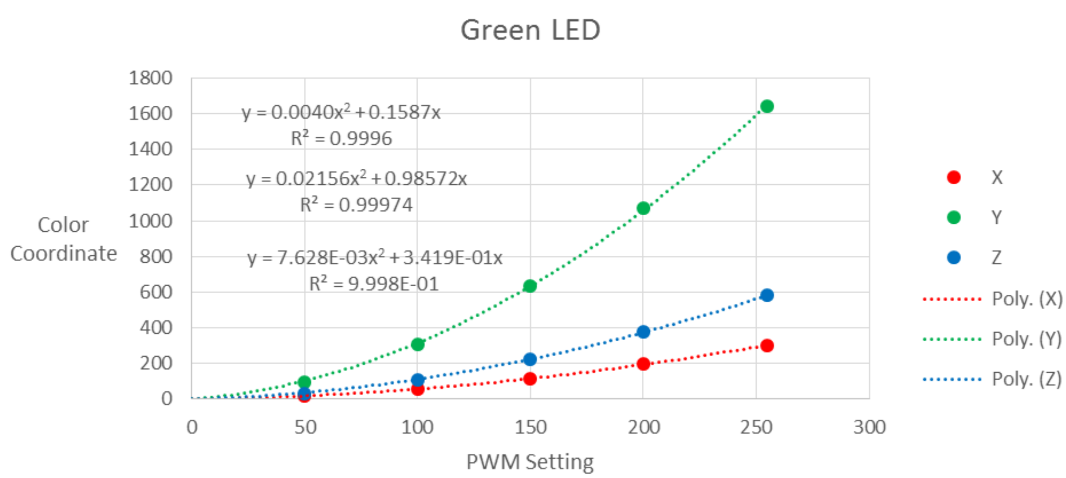


Fig. A-5 Green LED calibration curves and quadratic curve fits with R^2 values

Figure A-5 shows the quadratic fit expressions that give the LED CIE XYZ coordinates for the LED at variable PWM settings. The CIE XYZ coordinate expressions are given in the order y = X, y = Y, and Y = Z.

Outdoor LED Average Illuminance Values

Table A-6 gives the average of LED illuminance measured before and after each day of outdoor testing.

Table A-6 Average of LED illuminance measured before and after each day of outdoor testing

Subject no.	Date	Average green luminance (cd/m2)	Average red luminance (cd/m2)	Average white luminance (cd/m2)	Average amber luminance (cd/m2)	Average blue luminance (cd/m2)
1	12/4/2015	1.198E+05	5.325E+04	1.479E+05	2.641E+04	1.217E+04
2	12/4/2015	1.198E+05	5.325E+04	1.479E+05	2.641E+04	1.217E+04
3	12/8/2015	1.186E+05	5.402E+04	1.366E+05	2.642E+04	1.134E+04
5	12/7/2015	1.152E+05	5.288E+04	1.385E+05	2.662E+04	1.205E+04
6	12/7/2015	1.152E+05	5.288E+04	1.385E+05	2.662E+04	1.205E+04
7	12/8/2015	1.186E+05	5.402E+04	1.366E+05	2.642E+04	1.134E+04
8	12/8/2015	1.186E+05	5.402E+04	1.366E+05	2.642E+04	1.134E+04
9	12/8/2015	1.186E+05	5.402E+04	1.366E+05	2.642E+04	1.134E+04
10	12/9/2015	1.202E+05	5.431E+04	1.334E+05	2.609E+04	1.111E+04
11	12/9/2015	1.202E+05	5.431E+04	1.334E+05	2.609E+04	1.111E+04
12	12/9/2015	1.202E+05	5.431E+04	1.334E+05	2.609E+04	1.111E+04
13	12/10/2015	1.242E+05	5.434E+04	1.381E+05	2.627E+04	1.090E+04
14	12/10/2015	1.242E+05	5.434E+04	1.381E+05	2.627E+04	1.090E+04
15	12/10/2015	1.242E+05	5.434E+04	1.381E+05	2.627E+04	1.090E+04
16	12/10/2015	1.242E+05	5.434E+04	1.381E+05	2.627E+04	1.090E+04

Table A-6 Average of LED illuminance measured before and after each day of outdoor testing (continued)

Subject no.	Date	Average green luminance (cd/m2)	Average red luminance (cd/m2)	Average white luminance (cd/m2)	Average amber luminance (cd/m2)	Average blue luminance (cd/m2)
17	12/11/2015	1.212E+05	5.623E+04	1.384E+05	2.539E+04	1.164E+04
18	12/11/2015	1.212E+05	5.623E+04	1.384E+05	2.539E+04	1.164E+04
19	12/11/2015	1.212E+05	5.623E+04	1.384E+05	2.539E+04	1.164E+04
20	12/11/2015	1.212E+05	5.623E+04	1.384E+05	2.539E+04	1.164E+04
21	12/11/2015	1.212E+05	5.623E+04	1.384E+05	2.539E+04	1.164E+04
22	12/15/2015	1.195E+05	5.498E+04	1.364E+05	2.649E+04	1.149E+04
23	12/15/2015	1.195E+05	5.498E+04	1.364E+05	2.649E+04	1.149E+04
24	12/15/2015	1.195E+05	5.498E+04	1.364E+05	2.649E+04	1.149E+04
25	12/15/2015	1.195E+05	5.498E+04	1.364E+05	2.649E+04	1.149E+04
26	12/16/2015	1.214E+05	5.431E+04	1.354E+05	2.631E+04	1.172E+04
27	12/16/2015	1.214E+05	5.431E+04	1.354E+05	2.631E+04	1.172E+04
28	12/16/2015	1.214E+05	5.431E+04	1.354E+05	2.631E+04	1.172E+04
29	12/16/2015	1.214E+05	5.431E+04	1.354E+05	2.631E+04	1.172E+04

Participants tested on the same day show the same average illuminance. The average illuminance variation over the course of a day's testing was less than 3.3%. A neutral density filter was used to measure LED illuminance. The attenuation factor of the filter was x12.174; this factor has been applied to the illuminance values to give the actual illuminance at the distance of the light spectrophotometer from the LED. For calibration measurements, the distance of the spectrophotometer from each LED is given in Table A-7.

Table A-7 Calibration distance for each LED

LED color	Green	Red	White	Amber	Blue
Distance (m)	1.880	1.829	1.778	1.803	1.829

INTENTIONALLY LEFT BLANK.

List of Symbols, Abbreviations, and Acronyms

3-D	3-dimensional
CIE	International Commission on Illumination
fc	foot-candle
LED	light-emitting diode
lm	lumen
MARPAT	Marine Pattern
OWL	one-way luminescence
PWM	pulse-width modulators
RGB	red, green blue
VDC	volts direct current

1 DEFENSE TECHNICAL
(PDF) INFORMATION CTR
DTIC OCA

2 DIR ARL
(PDF) IMAL HRA
RECORDS MGMT
RDRL DCL
TECH LIB

1 GOVT PRINTG OFC
(PDF) A MALHOTRA

1 ARL
(PDF) RDRL HRB B
T DAVIS
BLDG 5400 RM C242
REDSTONE ARSENAL AL
35898-7290

8 ARL
(PDF) SFC PAUL RAY SMITH
CENTER
RDRL HRO COL H BUHL
RDRL HRF J CHEN
RDRL HRA I MARTINEZ
RDRL HRR R SOTTILARE
RDRL HRA C A RODRIGUEZ
RDRL HRA B G GOODWIN
RDRL HRA A C METEVIER
RDRL HRA D B PETTIT
12423 RESEARCH PARKWAY
ORLANDO FL 32826

1 USA ARMY G1
(PDF) DAPE HSI B KNAPP
300 ARMY PENTAGON
RM 2C489
WASHINGTON DC 20310-0300

1 USAF 711 HPW
(PDF) 711 HPW/RH K GEISS
2698 G ST BLDG 190
WRIGHT PATTERSON AFB OH
45433-7604

1 USN ONR
(PDF) ONR CODE 341 J TANGNEY
875 N RANDOLPH STREET
BLDG 87
ARLINGTON VA 22203-1986

1 USA NSRDEC
(PDF) RDNS D D TAMILIO
10 GENERAL GREENE AVE
NATICK MA 01760-2642

1 OSD OUSD ATL
(PDF) HPT&B B PETRO
4800 MARK CENTER DRIVE
SUITE 17E08
ALEXANDRIA VA 22350

ABERDEEN PROVING GROUND

15 ARL
(PDF) RDRL HR
J LOCKETT
P FRANASZCZUK
K MCDOWELL
K OIE
RDRL HRB
D HEADLEY
RDRL HRB A
J FAUGHN
RDRL HRB BA
B VAUGHAN
RDRL HRB C
J GRYNOVICKI
RDRL HRB D
C PAULILLO
RDRL HRF A
A DECOSTANZA
RDRL HRF B
A EVANS
RDRL HRF C
J GASTON
P FEDELE
RDRL HRF D
A MARATHE
C STACHOWIAK